

Atmospheric Multipath Effects Prediction for Army Communications Links

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Introduction

Army tactical communications at echelons brigade and above are dependent on line-of-sight (LOS) radio links. As current military doctrine stresses the requirement to rapidly deploy to meet a range of threats at locations worldwide, the Army cannot utilize a fixed infrastructure consisting of coaxial or fiber cable as is used in the commercial sector. Given the requirement to deploy worldwide, the propagation environment and resulting link reliability is an issue of serious concern to Army communications-systems planners. This concern becomes even greater in light of current initiatives to gain additional system capacity through modification of legacy systems and insertion of evolving communications system technology. In response to serious fading problems encountered during Operation Desert Storm [1], the U.S. Army Communications-Electronics Command (CECOM), in cooperation with the Project Manager, Joint Tactical Area Communications Systems (PM JTACS), initiated several efforts that addressed the subject of LOS propagation reliability. These efforts resulted in enhanced network planning and management tools that accounted for the impacts of climate-induced fading and improved operational procedures for establishing LOS links [2, 3, 4].

The link propagation reliability associated with microwave line-of-sight fading, caused by atmospheric layering, changes from month to month as temperature, humidity, and wind patterns change. Commercial practice has been to design links using the propagation reliability for the worst month of the year. The assumption there is that the links will be in service for many years and will operate on a year-round basis. This assumption is not valid for tactical links that have a transient existence. This paper extends the previous CECOM work and describes propagation reliability for links that must be highly reliable and may be in service for as short a time as an hour. This is accomplished by providing a bad-hour probability of fading for a calendar month. A bad hour is defined as the hour with the largest concentration of fading in a calendar month. The predicted concentration is to be viewed as an average over many years for a calendar month. The purpose of this paper is to describe these new reliability concepts and a model for predicting bad-hour reliability. The model can be used for narrowband radio channels and in some cases for wideband digital-radio channels when the dispersive fade margin is much larger than the thermal-noise fade margin [5].

Army Tactical Communications

Legacy Systems. The Army's Area Common User System (ACUS) consists of the Mobile Subscriber Equipment (MSE) at echelons corps and below (ECB) and the Tri-Service Tactical Communications System (TRI-TAC) at echelons above corps (EAC). The MSE system is a fully automated area-common-user system providing voice and data communications within the corps structure and interoperability with adjacent corps and EAC forces, North Atlantic Treaty Organization (NATO) forces, and commercial networks. TRI-TAC is an automated switching service that provides both voice and data communications for theater tactical corps and above forces. It is a digital, secure, common-user network, which provides subscribers with connectivity to strategic systems, the MSE system, commercial networks, other services' systems, and allied networks.

Both MSE and TRI-TAC consist of digital switches that use time-division multiplexing operating at 16 or 32 kilobits per second (kbps). MSE switches are supported by transmission systems that range from 8 to 64 channels, while EAC is deployed with transmission systems that range from 4 to 144 channels. It is expected that information-transport requirements for the digitized battlefield will exceed the capacity of these legacy transmission systems. The future infrastructure must support anticipated requirements that will range from 1.544 megabits per second (Mbps) for extension nodes to 10 Mbps or greater for interswitch links. In anticipation of future needs for higher capacity, there is a CECOM Research, Development and Engineering Center (RDEC) effort for 45- and 156-Mbps systems.

PM JTACS is executing an ACUS modernization plan (MP) that will support the migration of the Army's ACUS to the Warfighter Information Network (WIN). WIN is a coherent information systems architecture needed to support the requirements of the 21st-century force (Force XXI). As part of the ACUS MP, existing GRC-226 and GRC-222 radios used for internodal connectivity will be replaced by a High-Capacity LOS (HCLOS) radio system providing additional throughput to support emerging requirements for the high levels of voice, data, video and imagery traffic and the introduction of asynchronous transfer mode (ATM) switching, also planned as part of the MP.

Battlefield Information Transmission System. The Battlefield Information Transmission System (BITS) is an umbrella program comprising the Digital Bat-

tlefield Communications (DBC) Advanced Technology Demonstration (ATD), SPEAKEASY, Commercial Communications Technology Laboratory (C2TL), Advanced Concepts and Technology (ACT II), and related programs. BITS will provide enabling technologies for ACUS and WIN.

A major thrust of BITS and the DBC ATD is a series of High-Capacity Trunk Radios (HCTRs) designed to provide greater capacities for the ACUS and to support requirements for a mobile Radio Access Point (RAP). The RAP, using the HCTR and advanced phased-array antenna technology, will provide on-the-move connectivity between highly mobile forces at brigade and the fixed ATM infrastructure. The HCTR research and development efforts will also help to define appropriate technology for the next-generation ACUS LOS radio.

The HCTR(-), with a performance goal of 45 Mbps and a range of 25 kilometers (km), will be demonstrated during the Division XXI Advanced Warfighting Experiment (AWE) to show the potential of ATM technology with MSE. The HCTR(-) is a commercially available product selected as the result of a market survey sponsored by the DBC ATD. The objective HCTR is a developmental effort and will provide a minimum throughput of 45 Mbps, in both stationary and mobile operation. The objective HCTR will be demonstrated in conjunction with the RAP during the Corps XXI AWE and Joint Warfighter Interoperability Demonstration (JWID) '99,

CECOM Propagation Reliability Background

An LOS propagation-reliability working group, convened by CECOM has developed a propagation-reliability model of clear-air multipath fading suitable for link engineering of LOS Army tactical radio [6]. This program was stimulated by reports from LOS operators indicating that path reliability on many of their radio links was a daily problem during operations in Southwest Asia (SWA). The climate in SWA and elsewhere is known to be difficult for LOS radio propagation because of the high incidence of clear-air refractive effects causing large and frequent reductions in received signal strength (RSS), referred to as multipath fading.

The ability of an LOS radio installation to withstand decreases in RSS is represented by its fade margin, i.e., the amount of power in dB by which the average RSS exceeds the receiver's threshold for a permissible bit-error-rate, say 10^{-5} . The propagation-reliability model for multipath fading relates fade

margin to path reliability with site-specific parameters of path length, frequency, and calendar-month climate factors [6, 7]. Link engineering is executed by calculating the fade margin required to obtain an objective path reliability for given parameter values. The link is satisfactorily engineered if its fade margin equals or exceeds the required fade margin. This propagation reliability model has been incorporated in a battlefield automated system, the JTACS Network Planning Terminal (NPT) [2, 3] for MSE. The propagation reliability is the complement of the probability of fading. For example, a probability of fading of 0.01 (one percent) corresponds to a propagation reliability of 0.99. All probabilities in this paper are expressed as fractions (not as percentages).

Climate Factors. The propagation reliability model describes the transmission effects of the atmosphere on LOS links at tactical radio frequencies. Horizontal layers of differing humidity and temperature provide the mechanism for multiple rays from the transmitter to reach the receiving antenna. The received power during such **multipath** propagation varies rapidly in time (fades) because of the interference between the multiple rays. Superimposed on this fast fading is a slower variation associated with ducting.

The effects of geophysical and meteorological variables are consolidated into an empirical coefficient, the climate factor, because analytical description of these effects is intractable. Values for the climate factor range from 0 to about 100. The climate factors pertain to the existence of horizontal atmospheric layers of differing humidity and temperature. Fading can vary from insignificant at freezing temperatures to substantial at warm temperatures. There is monthly variation in the amount of fading even in climates where fading is present year-round. Monthly climate factors have been developed for the NPT [7]. There can also be significant hourly concentration in a fading month [8]. A model of the hourly concentration effect is introduced and applied in this paper.

Deep-Fade Region

Historically, parameters in the probability of fading have been defined in terms of equations for the **deep-fade** region where the received signal has a value that is much smaller than the value of the signal in the absence of fading. This has come about because much of the development of the probability of fading has been associated with commercial radio systems that can operate reliably in the presence of large re-

ductions of RSS (deep fades). The signal strength in the equations in this paper is described in terms of a fade depth (A)

$$A = -10 \log (\text{normalized power}) \quad (1)$$

where normalized power describes the received signal as a fraction of the received power in the absence of fading. For example, a normalized power of 0.01 corresponds to a fade depth of 20 dB. The calendar-month probability-of-fading equations developed by CECOM classify fades as deep when A is 25 dB or greater.

The mathematical expression for the calendar-month probability of fading in the deep fade region is [6]

$$P_m(A) = C_m K_{\text{link}} 10^{-A/10}, A \geq 25 \quad (2)$$

This is the probability that the received signal has faded to depth A or more. The link parameter K_{link} contains the path length (D, in km) and the radio frequency (F, in GHz)

$$K_{\text{link}} = 10^{-7} 12D36 F^{0.89} \quad (3)$$

The calendar-month climate factor C_m is obtained from charts or computer databases [7]. Descriptive categories of climate in terms of C_m are 1 (average), 10 (difficult), and 100 (very difficult).

Shallow-Fade Region

Tactical wireless communications links are designed for parameter values different from those for commercial links. The probability of fading in the shallow-fade region, $A < 25$ dB, is important for the design and operation of tactical links. The shallow-fade calendar-month probability of fading developed by CECOM [6, 9], based on international information, is

$$P_m(A) = 1 - \exp(-10^{-A} q(A)/20), A < 25 \quad (4)$$

where

$$q(A) = 2 + K(A)(q_t + R(A)) \quad (5)$$

$$K(A) = 10^{-0.016 A} (1 + 0.3 10^{-A/20}) \quad (6)$$

$$R(A) = 4.3 (10^{-A/20} + (A/800)) \quad (7)$$

$$q_t = ((r - 2)/K(25)) - R(25), q_t > -2 \quad (8)$$

$$r = -0.8 \log [-\ln(1 - P_m(25))] \quad (9)$$

where $P_m(25)$ is obtained from the deep-fade probability of fading.

Defocusing Region

It is common knowledge that during periods of heavy fading the average value of the received signal can become smaller than the value of the received signal in the absence of fading. This depression of the received signal is associated with strong atmospheric layering (ducting). To allow representation of possible defocusing during the bad hour, the description in this paper of the probability of fading is split into three regions. Fading more severe than that described by the Rayleigh distribution is in the defocusing region (see Figure 1). The expressions for the fading probabilities in the deep-fade and shallow-fade regions in Figure 1 remain as in the previous sections. Mathematically, the shallow-fade equation applies when $r < 2$. The shallow-fade equation becomes the Rayleigh distribution when $r = 2$.

The working hypothesis in this paper is that the fading probability in the defocusing region can be represented by a Rayleigh distribution with a smaller (depressed) root-mean-square (rms) value. This is a physically reasonable approach that permits more realistic modeling of fading in the defocusing region than was previously possible. It would be desirable to perform analysis of fading data to test or modify the hypothesis.

The bad-hour probability of fading in the defocusing region, expressed a Rayleigh distribution with a depressed rms value, is

$$P_h(A) = 1 - \exp(-10^{-(A-DL)/10}), \text{ any } A \quad (10)$$

where DL is the defocusing loss in positive dB. The deep-fade expression corresponding to this is

$$P_h(A) = 10^{-(A-DL)/10}, (A-DL) > 25 \quad (11)$$

In terms of the calendar-month probability of fading, from Equation 2,

$$P_h(A) = 730 K_{mh} C_m K_{link} 10^{-A/10}, \text{ large } A \quad (12)$$

where K_{mh} is the fraction of the calendar-month fading contained in the bad hour. The factor 730 comes from the renormalization of probability (there are 730 hours in an average month, $365 \times 24/12$). The expression for DL, obtained by combining the above two equations, is

$$DL = 10 \log(730 K_{mh} C_m K_{link}), DL \geq 0 \quad (13)$$

The probability of fading is in the defocusing region when DL is positive. If DL is negative, then equa-

tions for the deep or shallow fading region must be used.

Parameter Values

The bad-hour fading fraction K_{mh} is certainly a function of meteorological variables. It has a relatively large value when the climate is average [8]. Conversely, it can be expected to have a relatively small value when many hours in a month contain severe fading. A meteorological description of K_{mh} requires a separate investigation, but we can use the above two statements to construct a representative equation for K_{mh} for use in illustrative application in this paper. The function that we construct has a value of b for an average climate ($C_m = 1$) and decreases to a value of a when C_m becomes large

$$K_{mh} = a + (b - a)/C_m, C_m > 0.1 \quad (14)$$

Measurements in the United States suggest that [8]

$$b = 0.2 \quad (15)$$

To obtain a value for a , we consider a hypothetical climate with a very large C_m , where fading is severe and approximately equal for four hours every day. Then all the fading in the month is contained in 121.7 hours of equal-intensity fading (from 1/6 of 730 hours in an average month). The fraction of fading in one hour is therefore (from 1/121.7)

$$a = 0.0082 \quad (16)$$

The behavior of our illustrative bad-hour fading fraction as a function of C_m for these coefficients is shown in Figure 2.

The value of $P_h(A)$ is much larger than the value of $P_m(A)$ for the same large value of A because of the concentration of fading in the bad hour and the renormalization of probability (the denominator in the probability becomes smaller by a factor of 730). This increase can be illustrated by considering an equivalent bad-hour climate factor (from Equation 12)

$$C_h = 730 K_{mh} C_m \quad (17)$$

Values of C_h as a function C_m , for K_{mh} , as described in Equations 14 to 16, are shown in Figure 3. The large values of C_h substantiate the need for a new description of the fading probability in the defocusing region. Furthermore, the implied large values of $P_h(A)$ suggest reconsideration of link engineering and the requirements for link performance.

Examples

We present fading probabilities for path lengths of 25 kilometers (maximum MSE link length) and 40 kilometers (maximum length of links for EAC use) to illustrate prediction and application of the probability of fading for a bad hour. The radio frequency in the examples is 5.0 GHz, in recognition of the suitability of frequencies in that neighborhood for high-capacity radio channels. The probabilities are presented for average climate ($C_m = 1$, Figure 4), difficult climate ($C_m = 10$, Figure 5), and very difficult climate ($C_m = 100$, Figure 6). The bad-hour fading fraction K_{mh} is obtained from Equation (14). Each figure shows calendar-month fading probability P_m and the corresponding bad-hour fading probability P_h for the two path lengths. The numbers on the probability curves identify path length. The letter m identifies curves of P_m , and the letter h identifies curves of P_h . The curve for the Rayleigh probability distribution (rms value equal to zero fade level), identified by the letter R , is included for comparison.

It is intuitively obvious that the probability of fading for a bad hour is larger than the probability of fading for a month because the latter can be viewed as the average over the hours in the month. The examples in Figures 4 through 6 allow numerical comparison. Suppose the links are designed such that P_m is 0.001 (propagation reliability of 0.999). Let the fade margin for this design be denoted by $A_{0.001m}$. The quantity of interest is the ratio P_h/P_m at $A_{0.001m}$. These ratios are listed in Table 1. The largest ratio is 156 for a 25-kilometer path in an average climate. Ratios for the other climates are smaller because the concentration of fading in a bad hour decreases as the climate becomes more severe.

Link-design issues for bad-hour performance are highlighted when the fade margin to achieve a certain transmission performance is plotted as a function of the desired value of P_h in Figure 7. The probability scale covers P_h values from 0.001 to 0.1, corresponding to propagation reliabilities of 0.999 to 0.9. The number on the left on each curve is the path length in kilometers. The number on the right is the value of C_m . A fade margin of over 50 dB is needed to achieve a bad-hour propagation reliability of 0.999 on a 40-kilometer link in a very difficult climate. Equipment may not support such large fade margins, and 0.999 reliability for a bad hour may be an unrealistic requirement.

Outage time instead of propagation reliability in a bad hour may be a way to address bad-hour trans-

Table 1. Comparison of Calendar-Month and Bad-Hour Fading

cm	D, km	$A_{0.001m}$, dB	P_h/P_m
1	25	14.7	156
1	40	22.4	145
10	25	25.3	20
10	40	32.7	20
100	25	35.3	7
100	40	42.7	7

mission performance. Fade margins as a function of allowed bad-hour outage time are shown in Figure 8. Curves for 15-kilometer links have been added in acknowledgment of the fact that link design for a bad hour may require shorter paths. The required fade margin for a 40-kilometer link in a very difficult climate is smaller than 40 dB when an outage of 100 seconds is allowed (propagation reliability of 0.972). The suitability of such a design depends on the composition of fade events (number and duration) contained in the 100 seconds, the type of communications traffic, and the network protocol. Criteria for transmission performance during a bad hour is an area for future work.

Conclusions and Recommendations

This paper has continued the evolution of CECOM propagation-reliability work by describing new reliability concepts and developing a new propagation-reliability model for links that may be in service in a bad hour. Examples show that links engineered for a monthly propagation outage may have a propagation outage from 7 to 156 times worse in the bad hour of the month, depending on the fading climate. This suggests reconsideration of link engineering to include link reliability for any hour in the month. For example, the nominal monthly link propagation-reliability objective of 0.999 may not be appropriate for every hour in the month.

Further research of the hourly propagation-reliability model and criteria for transmission performance during a bad hour are areas for future work. However, immediate application of the simple hourly link propagation-reliability model to existing and planned Army LOS radio systems is recommended.

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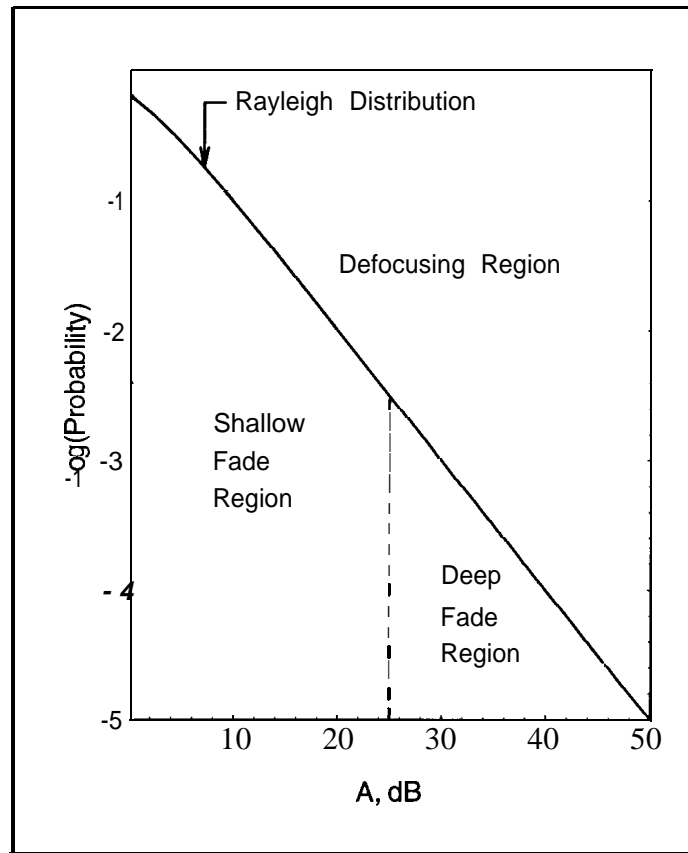


Figure 1

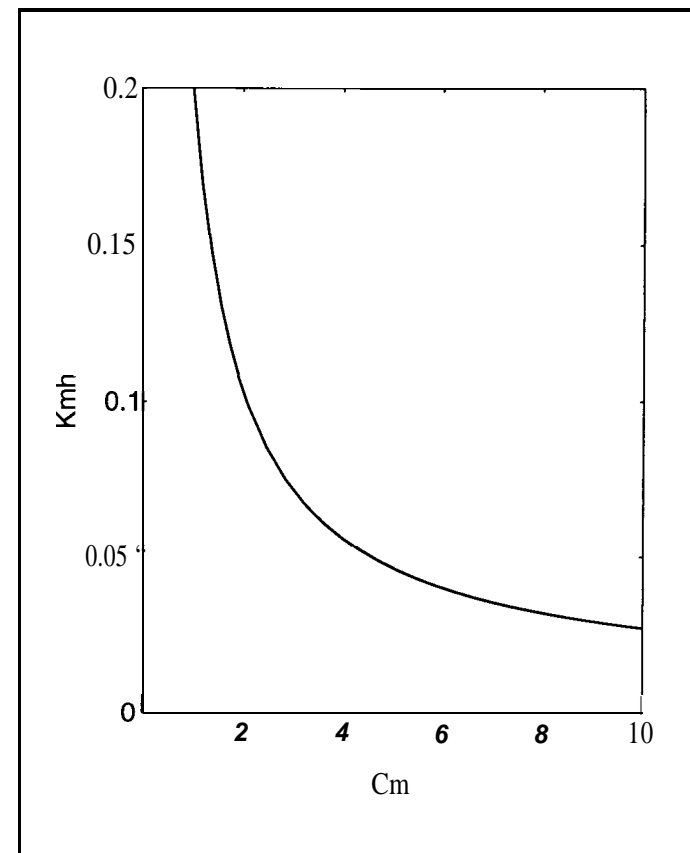


Figure 2

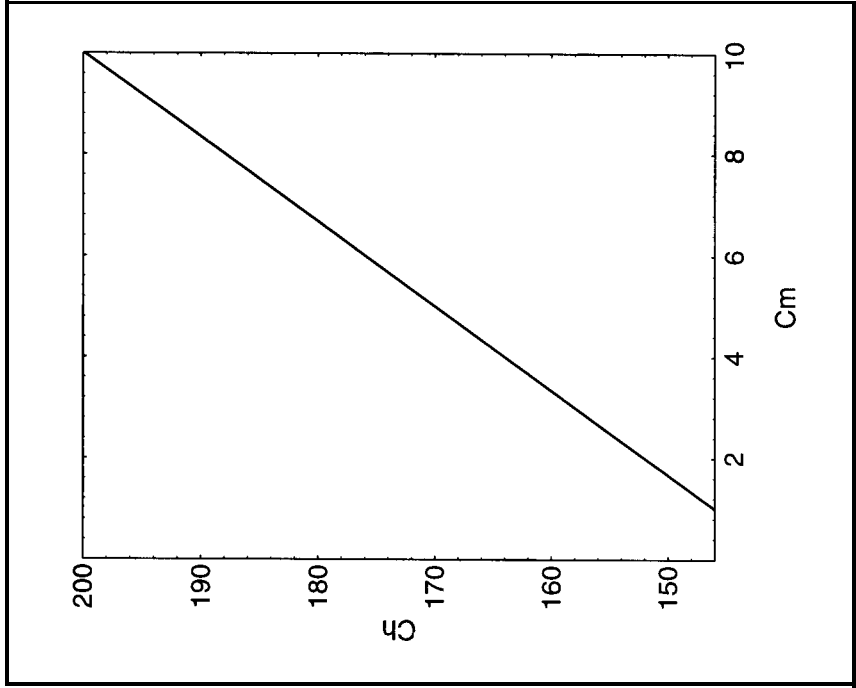


Figure 3

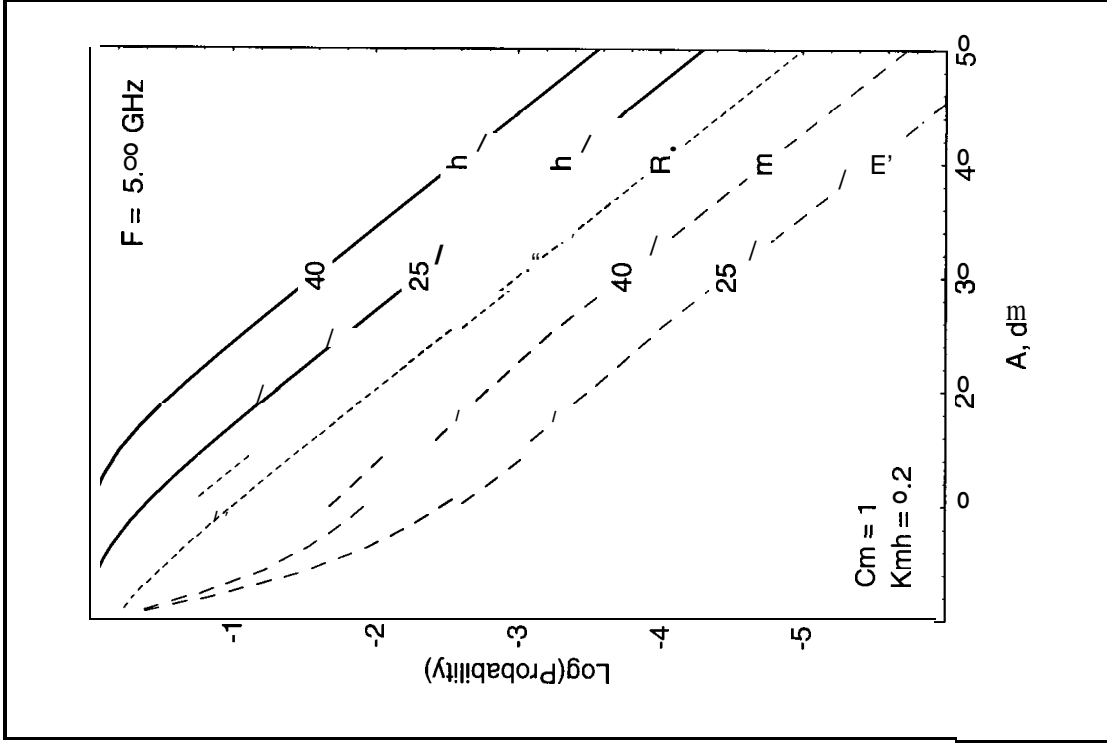


Figure 4

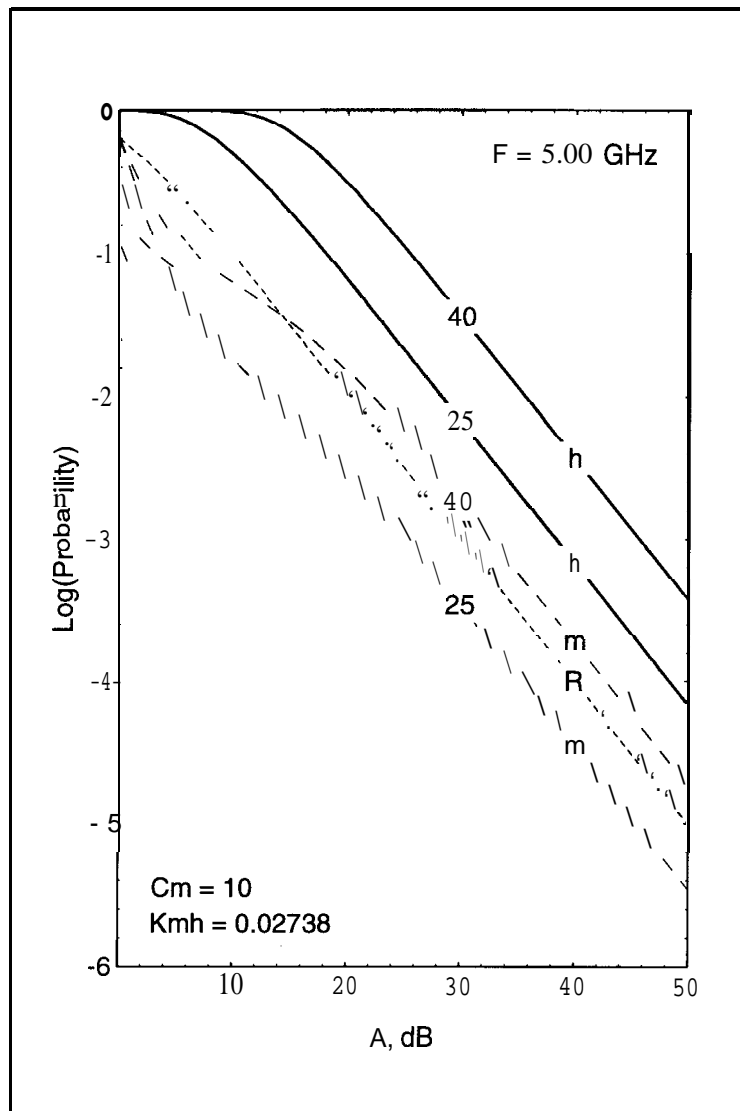


Figure 5

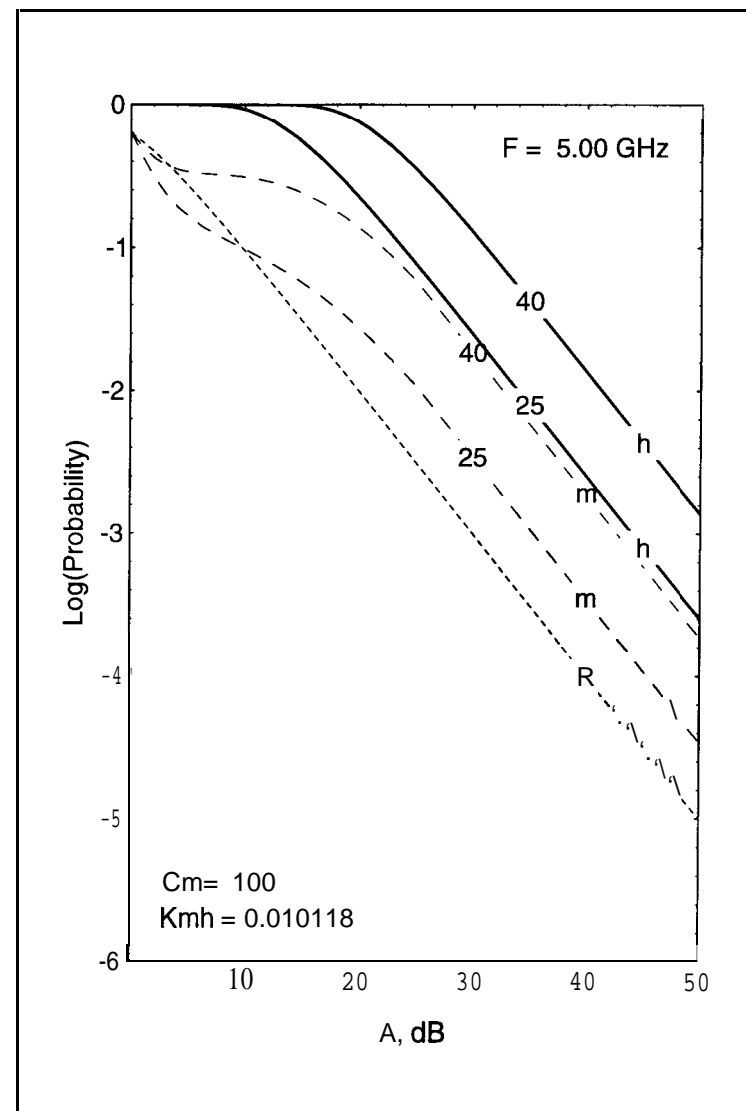


Figure 6

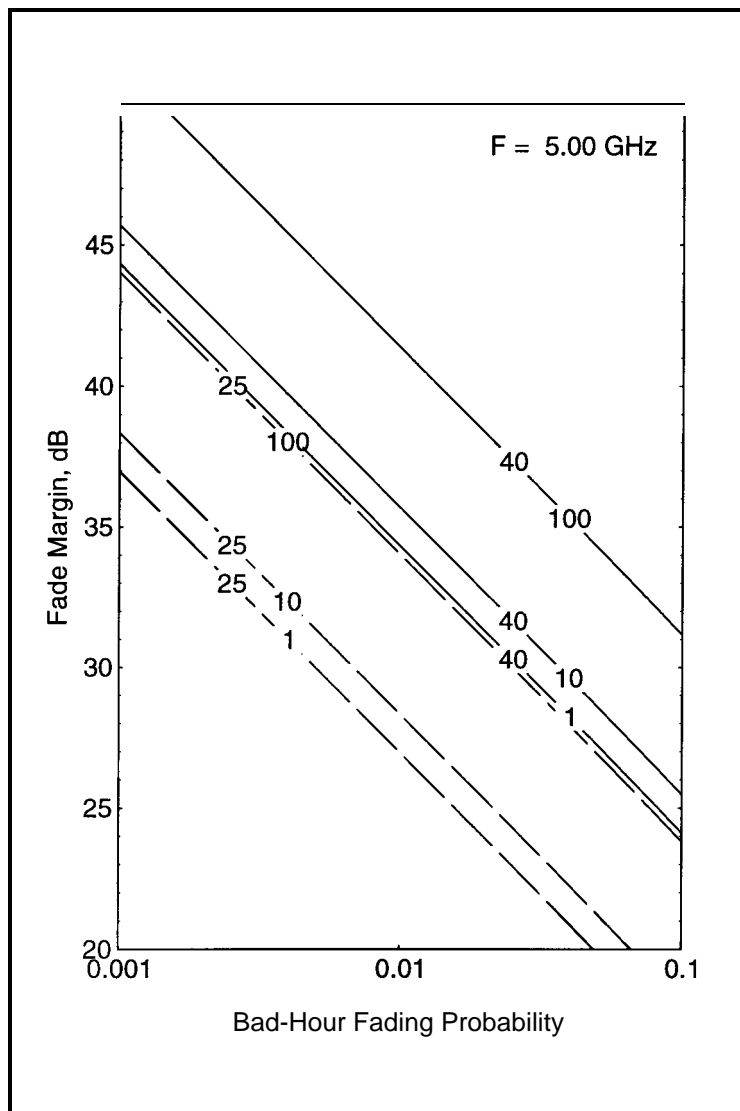


Figure 7

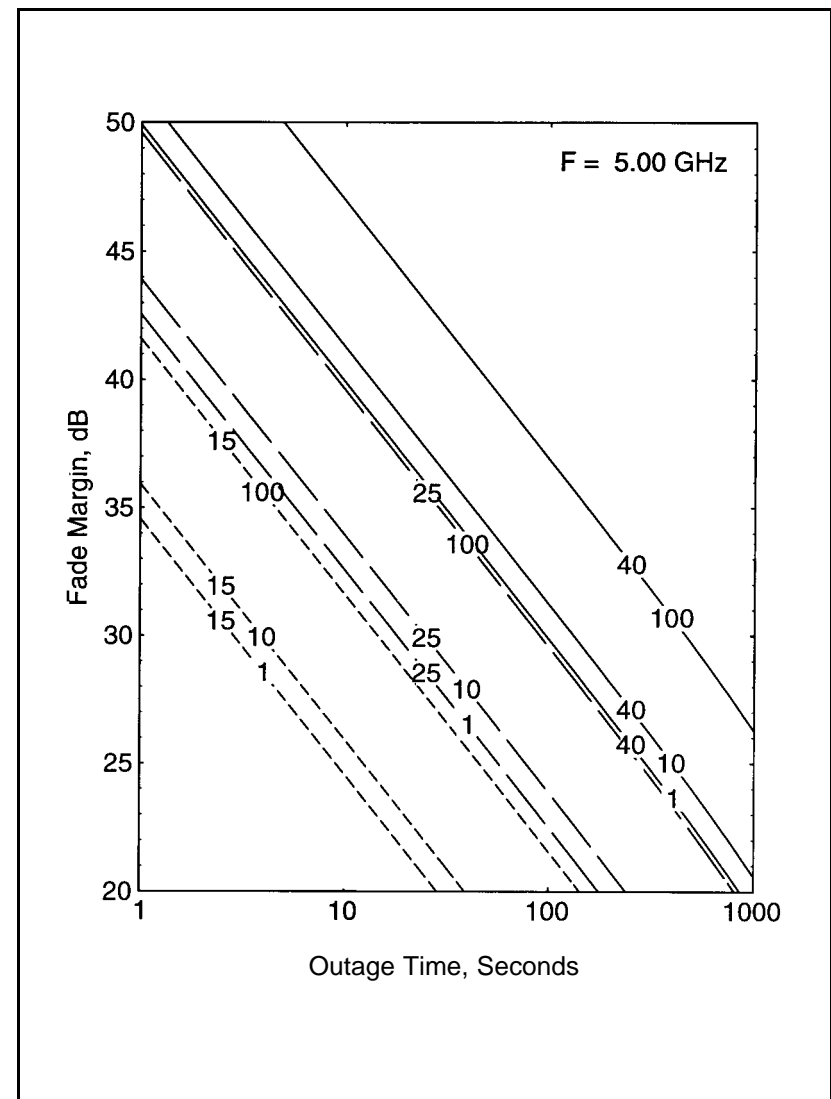


Figure 8